<u>Phase I Topical Report for DE-FG07-99ID13378</u>
May 31, 2000

Monitoring and Control Research Using a University Research Reactor

P.I. Robert M. Edwards, e48@psu.edu
Department of Mechanical and Nuclear Engineering
The Pennsylvania State University

<u>Summary:</u> The 1999 DOE NEER-funded project on "Monitoring and Control Research Using a University Reactor and SBWR Test-Loop" has completed all of its Phase 1 goals and is ready to proceed to the next phase.

<u>Discussion:</u>

Four goals were defined for Phase 1 and are briefly discussed below. The following eight forthcoming publications will further elaborate on the work:

1. Ceceñas-Falcón, M., and R.M. Edwards, "Stability Monitoring Tests Using a Nuclear-Coupled Boiling Channel," to appear in <u>Nuclear Technology</u> (July 2000).
2. Edwards, R.M., "Expansion of a Testbed for Advanced Reactor Monitoring and Control," <u>Trans. Amer. Nucl. Soc.</u> <u>82:</u>, San Diego, CA, (June 4-8, 2000).

The following papers are under final preparation for publication in the proceedings of "The Third American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies, NPIC&HMIT' 2000, Washington D.C., November 12-16, 2000. (It is expected that they will evolve into journal publications in the coming year.)

3. Ceceñas-Falcón, M., and R.M. Edwards, "Out-of-Phase BWR Stability Monitoring"
4. Shyu, S., and R.M. Edwards, "Optimized-Feedforward and Robust-Feedback Used in Integrated Automatic Reactor Control"
5. He, W., Z. Huang and R.M. Edwards "Experimental Validation of Optimized-Feedforward Control for Nuclear Reactors"
6. Huang, Z., and R.M. Edwards, "High-fidelity Hybrid Reactor Simulation of BWR"
7. Shaffer, R., and R.M. Edwards, "Experimental Validation of Robust Control for Nuclear Reactors"
8. Edwards, R.M. "Integration of a Thermal-Hydraulic Test-loop and University Research Reactor for Advanced Monitoring and Control Research"

The first goal was to upgrade the existing Experimental Changeable Reactivity Device (ECRD) and characterize its dynamics. (In the process of developing and approving the use of the new ECRD, it was determined that its name be changed from Secondary Control Rod as used in the proposal. The name change thus clearly distinguishes the ECRD from the control rods of the licensed monitoring, control and safety systems.) An ECRD is implemented as a TRIGA reactor moveable experiment where an aluminum tube containing an absorber material is positioned within the central thimble of the reactor by an experimental setup. With the completion of this goal, two ECRDs are now available for experimental monitoring and controls research. The original ECRD (ECRD #1) is worth approximately $0.35 and the newly constructed ECRD (ECRD #2) is worth approximately $0.94. ECRD #1 is used in experiments at power (up to 65%) where temperature changes produce significant reactivity changes. ECRD #2 was constructed for use at low power (less than 0.1%) where temperature change and its reactivity effect are negligible. The development of ECRD #2, which operates much more closely to the TRIGA reactor technical specification, was not a trivial exercise. The reactor facility staff performed a safety analysis, which was reviewed by the Penn State Reactor Safeguards Advisory committee. The reactor staff constructed the device and developed and executed the procedures to initially characterize its dynamics. ECRD #2 is worth approximately $0.94 and can be moved the length of its travel in approximately 3.5 seconds. An experimental worth curve shows that the ECRDs' differential worth is highest when approximately three-quarter inserted where the control rods do not shadow it.

The second goal was to convert an existing hybrid reactor simulation (HRS) capability using MATLAB real-time workshop to Windows NT platform. An HRS is implemented when a real-time simulation of BWR reactivity dynamics positions an ECRD and causes the TRIGA-reactor observed power response to mimic stability phenomena actually encountered in BWRs. Hybrid simulation in this context refers to the use of the research-reactor time response as an analog solution to the neutron kinetics equations. The TRIGA reactor's solution for the power response is used as an input signal to a real-time digital simulation of power-reactor thermal-hydraulics, which in-turn provides a reactivity feedback signal to the TRIGA through positioning of an ECRD. Figure 1 presents a top-level display of a HRS implemented in the current environment. The input signal to the block labeled ECRD+TRIGA is a reactivity rate signal in cents/second. A voltage signal is computed within the block and sent to the ECRD motor drive where it is processed as a velocity command. The reactor power output signal of the block is obtained by digitizing a voltage from a micro-micro ammeter driven by a CIC. All input and output signals used by the experimenter are independent and isolated from the licensed digital control and analog safety system.

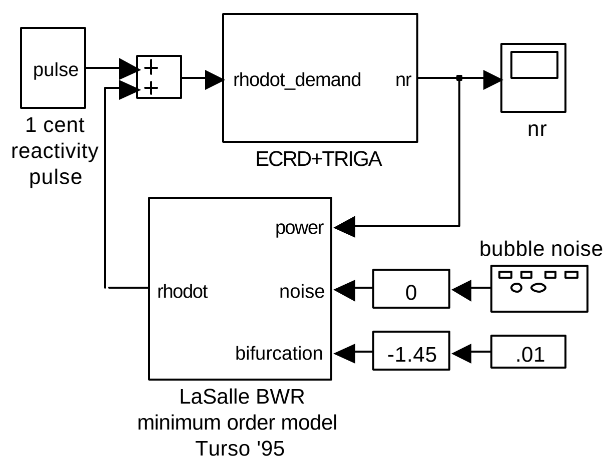

Fig 1: SIMULINK model of BWR Reactivity Feedback

The previously developed HRS used a now obsolete UNIX-network microprocessor-based control system. The conversion to the PC platform was needed to obtain currently available high performance computing to achieve real-time performance of high fidelity boiling channel simulations, as well as better supported application software. A Pentium 550 MHz and an AMD 1000 GHz PC computer were obtained and can be operated in two configurations for experiments. A National Instruments data acquisition card is installed in the AMD computer. It can be operated in a standalone mode where the graphical user interface and real-time application operate on the same computer using the MATLAB real-time workshop windows real-time target option. The second mode uses the MATLAB xPC real-time target option where a special real-time operating system is loaded on the AMD and it communicates with a windows-based graphical user interface on the Pentium computer. As more sophisticated graphical information displays are developed in Phase 2, it is anticipated that the second mode with both computers will be essential to maintain real-time performance while generating more sophisticated real-time graphics.

In addition to converting the previous HRS simulation, other important HRS experiments involving optimal control, robust control, and optimized feed-forward control were also readily converted to the PC platform.

The third goal was to develop real-time detailed simulation of commercial BWR boiling channels and modal kinetics in the HRS. Ceceñas-Falcón's boiling channel model, described in Reference 1, was converted to the real-time execution requirements of the MATLAB real-time workshop. This conversion required extensive revision of MATLAB m-file programming to required SIMULINK C-mex S-function programming. The converted model can now be readily incorporated in HRS simulation. A block representing a detailed boiling channel model simply replaces the block labeled "minimum order model" in Figure 1. The boiling channel models for Vermont Yankee and LaSalle utilize 20 axial nodes to implement nonlinear first-principles conservation of mass, momentum, and energy equations. The model makes extensive use of water and steam properties tables and is thus computationally intensive. Nonetheless, the model's real-time performance on the AMD 1000 GHz computer is excellent and readily allows the simulation of two (or more) boiling channels for hybrid reactor simulation of BWR out-of-phase oscillations. Out-of-phase BWR behavior is implemented in the HRS by using the TRIGA reactor to obtain an analog solution of the in-phase (or fundamental mode) dynamics while the out-of-phase (or first-harmonic mode) amplitude is simulated. The coupling of the simulated out-of-phase mode to the TRIGA generated in-phase mode is achieved by appropriately modifying the reactivity rate signal to the ECRD. Simulated void reactivity feedback paths are provided for each of the fundamental and first-harmonic modes.

The fourth goal was to develop an initial hybrid testloop simulation (HLS) to utilize simulation of point kinetics interfaced to the HLS heater rods. The Penn State thermal-hydraulic testloop mimics the boiling phenomena of a Simplified Boiling Water Reactor (SBWR), an advanced reactor design concept, in a unique atmospheric pressure facility where flow visualization is afforded by borosilicate glass piping. Electrically heated rods take the place of the nuclear reactor fuel. The design and construction of the testloop has been a multiyear undergraduate design project that is entering an operational phase with manual or open-loop control of the electrically heated rods.

The initial HLS was implemented using the existing testloop computer and data acquisition system, a 250 MHz Pentium computer. The testloop computer uses data-acquisition cards from Computer Boards Inc, which are not all currently supported for use with the MATLAB real-time workshop. The initial HLS was implemented with National Instruments LabView software. LabView provides extensive graphical interface development tools and includes the capability to create a virtual interface for world-wide-web based experiments. Some work in a separate DOE reactor-sharing project at Penn State has already demonstrated the LabView web-based interface to an undergraduate reactor oscillator experiment. An effort to extend the HLS operation to the web was not identified as a goal of the proposal, but it will be pursued provided that it does not interfere with achieving Phase 2 goals or provided that alternate funding can be obtained. An example of using LabView for web-based virtual experiments that we look to can be found at http://vll.phys.dal.ca/.

Although LabView provides a rich operator interface environment, it does not appear to presently offer MATLAB's ease of implementing complex real-time computationally intensive simulations, such as a boiling channel. (The LabView interface for the initial HLS is shown in Figure 2.) Conversely, MATLAB provides a rich environment for implementing real-time computationally intensive simulations but does not appear to offer LabView's ease of implementing a sophisticated operator interface. Phase 2 work will seek a solution for obtaining both computationally intensive real-time hybrid simulations with a good operator interface.

In the initial LabView-based HLS, measurements of void fraction and temperature from thermocouples embedded in the heater rods provided feedback signals to adjust reactivity of a simulated reactor kinetics response. The simulated reactor kinetics response was then used to set the electrical power delivered to the heater rods. A simulated control rod position is provided for manual control of the HLS in an analogous manner as a reactor. As the operator moves the simulated control rod, the physical fuel-temperature and void measurements generate simulated reactivity feedback to bring the HLS to new stable power levels. Some interesting opportunities for additional research to enhance the HLS include distributed-parameter estimation of void distribution along the length of the fuel bundle and processing of the temperature measurements to identify and filter the effects of spurious or failed thermocouple readings. Distributed-parameter estimation of void-fraction distribution would benefit from the development and validation of a first-principles (or experimentally determined) boiling channel model of the testloop, which is also needed in the Phase 3 effort to implement an out-of-phase HLS.

Conclusion:

The 1999 DOE NEER-funded project on "Monitoring and Control Research Using a University Reactor and SBWR Test-Loop" has completed all of its Phase 1 goals and is ready to proceed to the next phase. Phase 2 is scheduled to run from July 1, 2000 to December 31, 2000. The Phase 2 goals are 1) to evaluate on-line uncertainty monitoring for robust control validation and 2) to develop enhanced information displays to convey real-time information of HRS with out-of-phase stability characteristics.

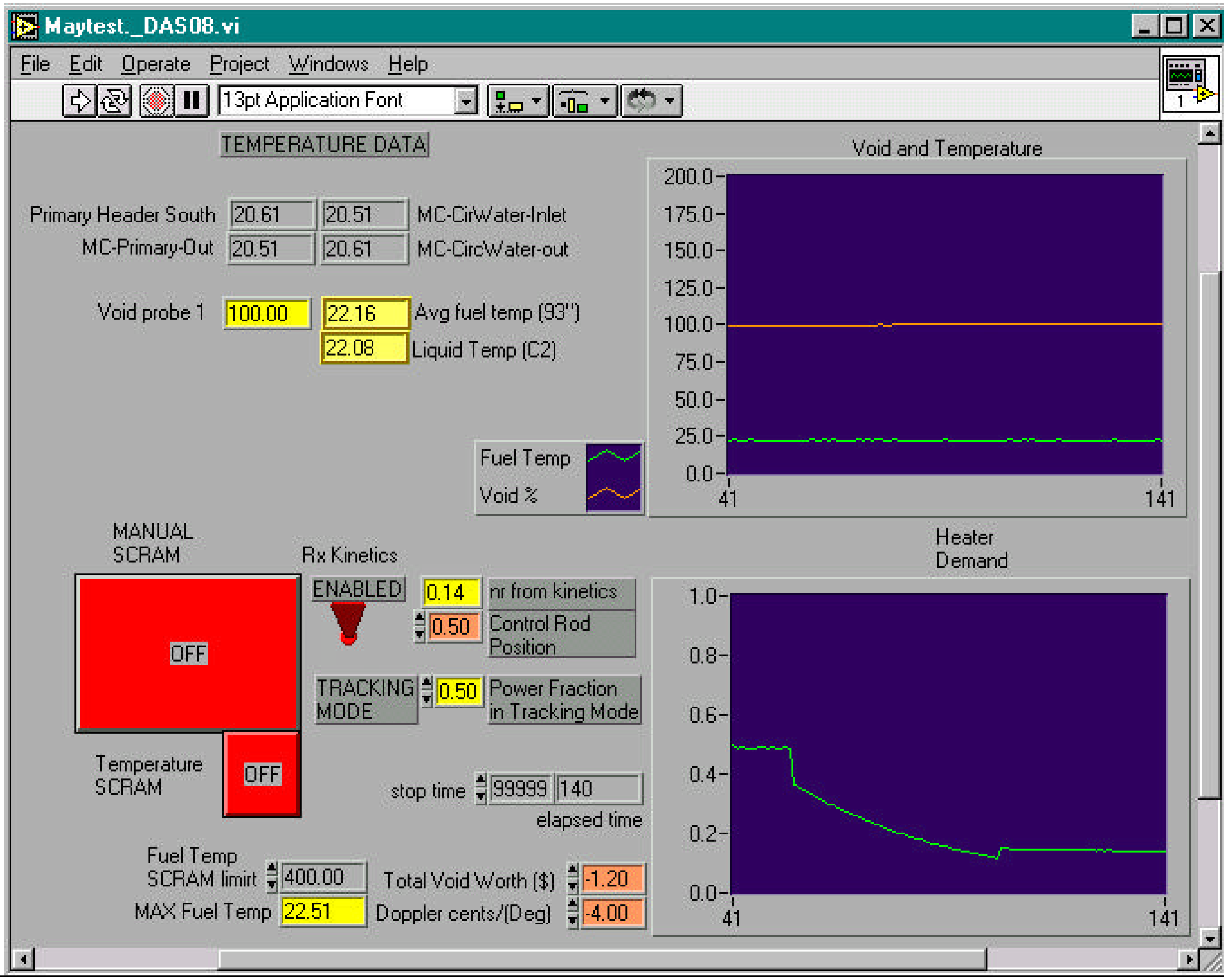

Figure 2: Hybrid Testloop Simulation (HLS) LabView Interface

(Note: This particular screen was generated offline with the loop shutdown, without power applied to the rods and thus without significant reactivity feedback. At t=41 seconds, the reactor kinetics is enabled at a power fraction of 0.5. At t=~ 50 seconds, the simulated control rod was moved to induce a -0.20$ reactivity insertion. At t=~100 seconds the simulated control rod was moved back to its original position. The Doppler feedback was made arbitrarily large to induce reactivity noise from noisy thermocouple readings about ambient conditions.)